SECURITY INFORMATION

c.1

CONFIDENTIAL

Copy 5
RM E52D18

NACA RM E52D18

NACA

RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AXIAL-FLOW COMPRESSOR

STATOR BLADES DESIGNED TO OBTAIN HIGH TURNING

ANGLES BY MEANS OF BOUNDARY-LAYER SUCTION

By G. R. Costello, R. L. Cummings, and G. K. Serovy

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

CLASSIFICATION CHANGED

To UNCLASSIFIED

By authority of NACA Res abs + RN-126 Date effective Apr. 15, 1958

AMT 5-8-58

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
June 27, 1952

CONFIDENTIAL

2548

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AXIAL-FLOW COMPRESSOR STATOR BLADES DESIGNED TO OBTAIN HIGH TURNING ANGLES BY MEANS OF BOUNDARY-LAYER SUCTION

By G. R. Costello, R. L. Cummings, and G. K. Serovy

SUMMARY

An investigation was conducted to determine the practicability of using blade boundary-layer control in order to obtain high turning angles in a stator-blade row. The slotted stator blades were designed by a potential-flow method for a 45° turning angle with low solidity using 1 percent boundary-layer bleed. These blades were installed in a 14-inch tip-diameter, single-stage compressor. Several slot-configurations designed to reduce the large secondary flows produced by the original blades were tested. These secondary flows caused high losses through the stator blade row. These losses must be reduced if such blading is to be practical. In addition, a means of boundary-layer control was installed on the hub ahead of the stator blades to improve the entrance conditions.

The over-all performance of the stage was obtained for a range of weight flows at each of three tip speeds with and without hub suction. These results together with wake surveys indicated that, although the design turning was obtained, the slots created large local static-pressure gradients which caused separation from the walls and greatly increased the secondary flows.

INTRODUCTION

A recent theoretical investigation (reference 1) indicated that use of boundary-layer control on the stators of the latter stages of a multistage compressor to obtain large increases in turning angles through these stators would improve the performance of the compressor by increasing the pressure ratio in the latter stages and broadening the operating range.

In order to evaluate the practicability of these blades by determining the quantity of boundary-layer bleed necessary to obtain these high turnings as well as the efficiency of these blades, a set of stator blades especially designed for boundary-layer bleed was installed in a variable-component, single-stage compressor. Various suction slot configurations on the blade surfaces were studied over a range of compressor speeds and weight flows. Because all slot configurations tested increased the secondary flows, particularly at the hub, boundary-layer bleed was introduced on the hub ahead of the stators in order to help control these flows. This investigation was conducted at the NACA Lewis laboratory. 2548

The variation of total-pressure ratio and efficiency with corrected weight flow is presented for the best slot configuration tested with and without hub boundary-layer control.

SYMBOLS

The following symbols are used in this report:

a	velocity of sound, ft/sec
c	blade chord, ft
M	Mach number
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
r	radius to blade element, ft
$\frac{U_t}{\sqrt{\theta}}$	equivalent tip speed corrected to NACA standard sea-level conditions, ft/sec
V	absolute air velocity, ft/sec
W	compressor weight flow, lb/sec
$\frac{W\sqrt{\theta}}{\delta}$	compressor weight flow corrected to NACA standard sea-level conditions, lb/sec
β	absolute air-flow angle measured from axis, deg
δ	ratio of inlet total pressure to NACA standard sea-level pressure
η_{ad}	adiabatic efficiency
θ	ratio of inlet total temperature to NACA standard sea-level temperature
σ	solidity, chord/blade spacing

Subscripts:

t	tip
0	measuring station at inlet tank (see fig. 5)
1	measuring station after rotor (1.22 in. upstream of stator-blade leading edge, see fig. 5)
2	measuring station after stator (1.50 in. downstream of stator-blade trailing edge, see fig. 5)

STATOR-BLADE DESIGN

The stator blades were designed by using the two-dimensional potential-flow method of reference 1 to obtain the tip and hub sections and fairing linearly between these stations. The sections were designed to turn the air 45° with an inlet-air angle of 45° and 1-percent boundary-layer bleed. The inlet Mach numbers were 0.6 at the tip and 0.7 at the hub. These conditions approximate the design rotor-exit conditions as given in reference 2. The blades were set in the case so that the entering air made the design angle with the blade chord at the design speed and weight flow. The hub and tip sections and their two-dimensional potential-flow velocity distributions are shown in figures 1 to 4.

The initial tests of this blade showed large wakes and therefore several slot configurations were tried. The "best" of these configurations was used in the performance tests.

APPARATUS

Flow Passage

The stator blades were installed in a 14-inch tip-diameter, variable-component, axial-flow compressor. A cross section of the flow passage is shown in figure 5. The guide vanes and rotor blades used were those of reference 2. The hub contour was the same as that of reference 2 to a point approximately 0.65 inch upstream of the stator-blade leading edge. Downstream of this point the hub radius was constant at 5.825 inches, giving a stator-blade hub-to-tip diameter ratio of 0.832. The downstream edge of the rotor was located approximately 0.100 inch from the stator-blade leading edge. The 0.06-inch clearance space between the rotor and the inner wall of the discharge passage was used as a hub suction slot for removing boundary-layer air immediately in front of the stator blades. Stator-blade hub clearance was 0.010 inch.

[redacted]

Compressor Installation

The compressor installation is shown schematically in figure 6. Air was drawn from the test cell into a depression tank through a standard thin-plate orifice mounted on the end of an orifice tank. In order to obtain uniform flow at the compressor inlet, a series of screens, filter paper, and a 3- by 3-inch honeycomb were located in the depression tank. Air was discharged from the compressor collector into the laboratory exhaust system.

2548

Individual tubes welded into the blade bases led to a common manifold for the application of suction to the stator-blade slots (see fig. 5). The manifold was connected through a calibrated orifice to the main exhaust system. Suction weight flow was controlled by a valve in the orifice line. Tubes fitted into the compressor rear bearing housing were used to apply suction to the hub slot. The suction air from the hub slot was discharged through a second manifold and a calibrated orifice to the main exhaust system. A valve in the orifice line was used to control the suction weight flow.

Instrumentation

Instrumentation for the determination of over-all and stator-blade performance was located in the depression tank, downstream of the rotor blades, and downstream of the stator blades. A summary of the instrumentation is given in table I.

Pressure and temperatures measured in the depression tank were assumed to be stagnation values. The thermocouples at station 2 were connected differentially with those in the depression tank so that a circumferentially averaged value of the temperature rise across the compressor could be calculated for each of the radial measuring stations.

Compressor weight flow was measured with a standard thin-plate orifice located at the inlet to the orifice tank. Calibrated orifices in the suction piping were used for measurement of the weight flows removed through the blade slots and the hub slot. Compressor speed was measured by a precision-type electronic tachometer.

PROCEDURE

Test Procedure

The first phase of the test program was an investigation of several blade-slot configurations in order to determine the location of slots and the quantity of suction necessary to most effectively reduce the

2548

stator-blade losses. The slot configurations considered are shown in the order of their use in figure 7. The first stator blades installed were slotted with the single 0.020-inch slot of configuration A. In order to test the other slot arrangements, only three blades were modified and the flow conditions were determined behind these blades. Performance for each slot configuration was determined at the design-equivalent tip speed of 836 feet per second and at a weight flow that gave approximately the design angle of attack at the mean radius of the stator blades. Blade suction was varied in order to determine the effect of the quantity of air removed on the blade performance; hub suction was not used. The blade-slot configuration F used for the major part of the investigation was the one which produced the most desirable flow pattern downstream of the stator blades as determined by total-pressure wake surveys. This configuration does not necessarily represent the optimum obtainable but was definitely the best investigated.

In the second phase of the program, a complete set of stator blades slotted as configuration F (fig. 7) was installed in the compressor, and over-all performance data were taken at equivalent tip speeds of 585, 753, and 836 feet per second. At each speed a complete range of weight flows was covered from the maximum that could be obtained with the constant inlet pressure of 25 inches of mercury absolute to the point of flow instability. For each speed, data were taken first without hub suction and then with approximately 2 percent of the inlet weight flow removed by hub suction. At each data point, the blade-suction weight flow was set so that the slots were choked in order to keep the radial distribution of suction weight uniform.

Calculation Methods

The total-pressure ratio used in this investigation was obtained from a mass-flow-weighted average of the isentropic energy input integrated across the flow passage (reference 3). The adiabatic efficiency used in evaluating the compressor performance was calculated from a mass-flow-weighted average of the total-temperature rise across the compressor and a mass-flow-weighted average of the isentropic power input (reference 3).

RESULTS AND DISCUSSION

Slot Configuration

When the stator blades with the original slot configuration A (fig. 7) were first tested in the compressor at design speed and weight flow, there was very little difference in the wakes with or without blade suction. Both wakes were very large. The turning angle was considerably less than design, which indicated that the flow had separated from the blade.

The slots on three blades were enlarged to 0.040 inch, which improved the wake at the pitch radius but made the wake at the hub and tip larger. When slots 0.080-inch wide were tried, the wake at the blade tip was very small but the wake at the hub was increased greatly, indicating that the boundary layer on the hub was flowing across the channel and up the suction surface of the blade and thereby causing the flow to separate. In an attempt to reduce the flow up the blade, the slot configurations D and E were tested, but little, if any, effect on the blade wake near the hub was noted.

In order to reduce the separation, two 0.020-inch slots, configuration F, were used. The design turning was obtained with these blades, and, although the wake was large, it was the smallest for all the blades tested. The wake was very similar in shape to that produced by the 0.080-inch slot but required much less air to be removed.

The remainder of the stator blades were slotted in this manner for the over-all performance tests. Also hub boundary-layer control by a slot located just upstream of the stators (see fig. 5) was installed to help control the blade wake at the hub.

Over-All Performance

In the initial testing various blade and hub-suction weight flows were used. The smallest wakes were obtained with the blade slots choked and with two percent of the total compressor weight flow being removed through the hub slot. These values were used in determining the over-all performance of the stage.

The over-all total-pressure ratio P_2/P_0 and adiabatic efficiency η_{ad} are plotted against corrected weight flow $\frac{W\sqrt{\theta}}{\delta}$ in figure 8, and the ratios of the suction weight flows to the total inlet weight flow are plotted against the corrected weight flow in figure 9. The over-all stage performance was quite poor when compared with the rotor guide-vane pressure ratio and efficiency as given in reference 4, indicating that although the design turning was obtained in the stators the losses were very high. The hub boundary-layer control had a small effect on efficiency at the high speeds but increased the efficiency considerably at the low speeds, and was most effective where the pressure ratio was small.

2548

Stator-Blade Wakes

The stator-blade wake (measured at station 2) with the blade slots choked and without hub suction for the design speed and weight flow is shown in figure 10, where the change in total pressure divided by the dynamic head $\frac{P_1-P_2}{P_1-p_1}$ for the six radial positions is plotted against circumferential distance in degrees from a point directly axial of the trailing edge of one blade to a point directly axial of the next blade. The mean flow angles vary only slightly from the axial direction so that a point directly downstream of the trailing edge of the blade would fall between 0° and 1° in figures 10 and 11. Figure 11 shows the wake at the same flow conditions as figure 10 but with 3-percent hub suction. The removal of the boundary layer on the hub reduced the peaks in the wake considerably, but in most of the channel the reduction was small.

The high-loss regions are not directly downstream of the trailing edge of the blade but are located at least 20 percent of the channel width from a position directly downstream of the trailing edge, indicating that the main loss does not arise from separation on the blade but probably from separation on the case and extremely large secondary flows (figs. 10 and 11).

The approximate streamlines in a two-dimensional potential flow past the hub section of the stators are shown in figure 12. In the neighborhood of the suction slots the streamlines near the suction surface of the blade curve sharply, which results in large local diffusion rates (as in the stream tube aa). These large diffusions apparently cause the flow to separate from the compressor case. Also where the streamlines curve sharply, the cross-channel static-pressure gradient is very large and therefore induces large secondary flows.

The existence of the large secondary flows and separated areas were indicated by hydrogen sulfide traces. One blade and one passage were coated with a thin film of lead oxide; and when the compressor was running at design conditions, hydrogen sulfide was introduced into the boundary layer on the inner case at a point approximately 1/4 inch downstream of the leading edge of the stator and 3/16 inch from the suction surface.

Without blade suction the lead sulfide traces on the case showed little, if any, deflection toward the suction surface of the blade. The streak lines in the white lead indicated the flow had separated from the blade surface just upstream of the first suction slot (fig. 13).

The traces with blade suction are shown in figure 14 where the area between the dashed line and the end of the blade indicates the area where

lead sulfide was formed on the blade. Figure 15 is a sketch of the traces on the inner case. The area enclosed by the dashed line indicates the area where the lead sulfide was formed on the case. The solid lines are the streak lines (similar to those in fig. 13) formed in the lead oxide by the scouring action of the air. In the channel near the slots the streak lines show that the flow has apparently separated from 2548
the case at the point indicated in figure 15. The high-loss regions in the blade wake surveys (figs. 10 and 11) are directly downstream of this point.

CONCLUDING REMARKS

This investigation of slotted stator blades designed for blade boundary-layer control has shown that large turning angles (at least 45°) can be obtained in a compressor stator with low-solidity blades. This turning was obtained by removing 2 to 3 percent of the air for blade boundary-layer control. However, the suction slots created high local static-pressure gradients which greatly increased the secondary flows and caused separation from the case so that the total-pressure losses through these stator blades were large. Consequently, the secondary flows and wall separation caused by the slots must be controlled by some means (such as distributed suction) if such stator blades are to be practical.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

REFERENCES

1. Sinnette, John T., Jr., and Costello, George R.: Possible Application of Blade Boundary-Layer Control to Improvement of Design and Off-Design Performance of Axial-Flow Turbomachines. NACA TN 2371, 1951.

2. Voit, Charles H., Guentert, Donald C., and Dugan, James F.: Performance of High-Pressure-Ratio Axial-Flow Compressor Using Highly Cambered NACA 65-Series Blower Blades at High Mach Numbers. NACA RM E50A09, 1950.

3. Mankuta, Harry, and Guentert, Donald C.: Investigation of Performance of Single-Stage Axial-Flow Compressor Using NACA 5509-34 Blade Section. NACA RM E8F30, 1948.

4. Standahar, Raymond, and Serovy, George K.: Some Effects of Changing Solidity by Varying the Number of Blades on Performance of an Axial-Flow Compressor Stage. NACA RM E52A31, 1952.

TABLE I - INSTRUMENTATION

Station	Radial measuring station (ft)	Measurement	Instrument	Circumferential position
0		Total pressure	Wall taps	2
		Total temperature	Thermocouple probe	4
1	0.5783 .5708 .5458 .5208 .4958 .4883	Total pressure	Hook-type total-pressure probe	1
		Flow angle	Claw-type probe	1
		Static pressure	Wedge-type static-pressure probe	1
2	0.5783 .5711 .5466 .5221 .4976 .4904	Total pressure	25-tube total-pressure rake	1
		Flow angle	Claw-type probe	1
		Static pressure	Wedge-type static-pressure probe	1
			Outer wall taps	4
			Inner wall taps	4
		Total temperature	4-tip thermocouple probe	4

2548

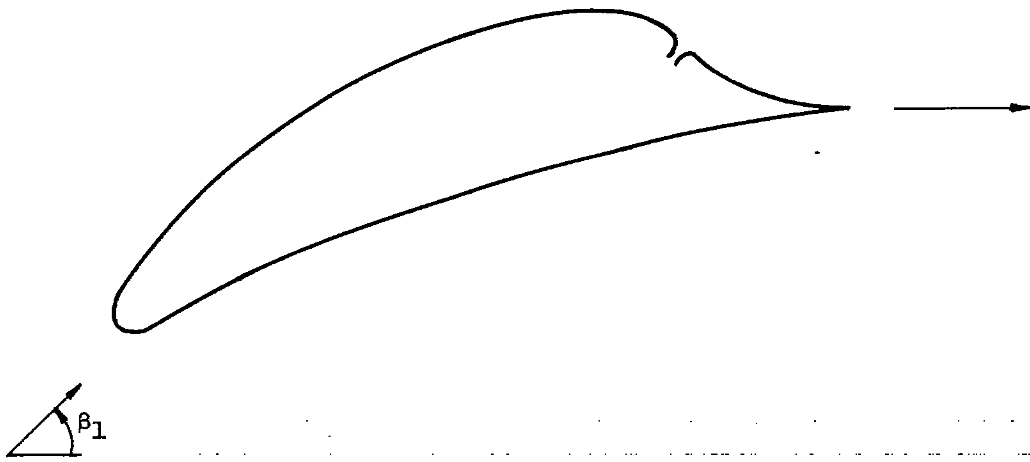


Figure 1. - Stator-blade profile at tip. r, 0.5833 feet; c, 0.1238 feet; σ, 0.81; M_1, 0.6; β_1, 45°; β_2, 0°.

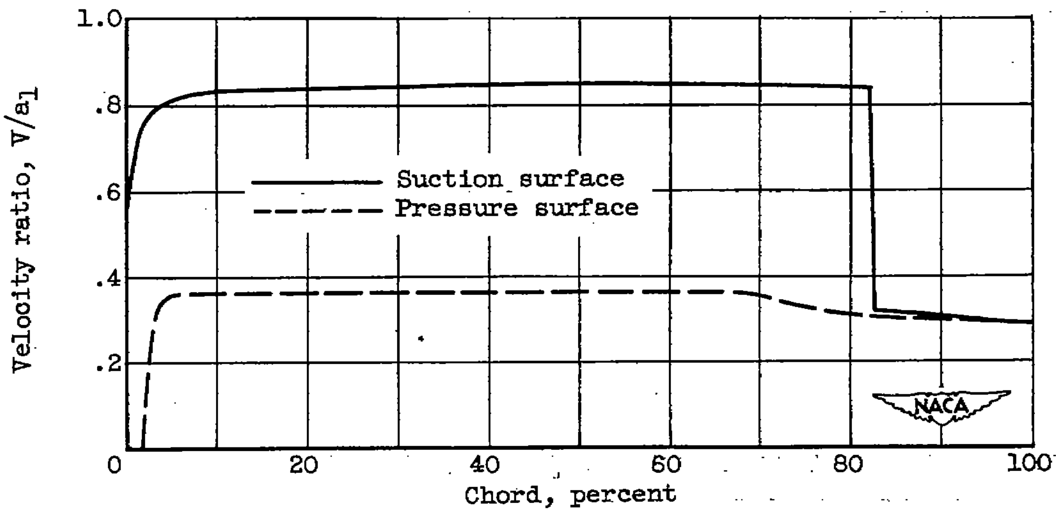


Figure 2. - Two-dimensional potential-flow velocity distribution on tip section of stator blade.

2548

Figure 3. - Stator-blade profile at hub. r, 0.4854 feet; c, 0.1238 feet; σ, 0.97; M_1, 0.7; β_1, 45°; β_2, 0°.

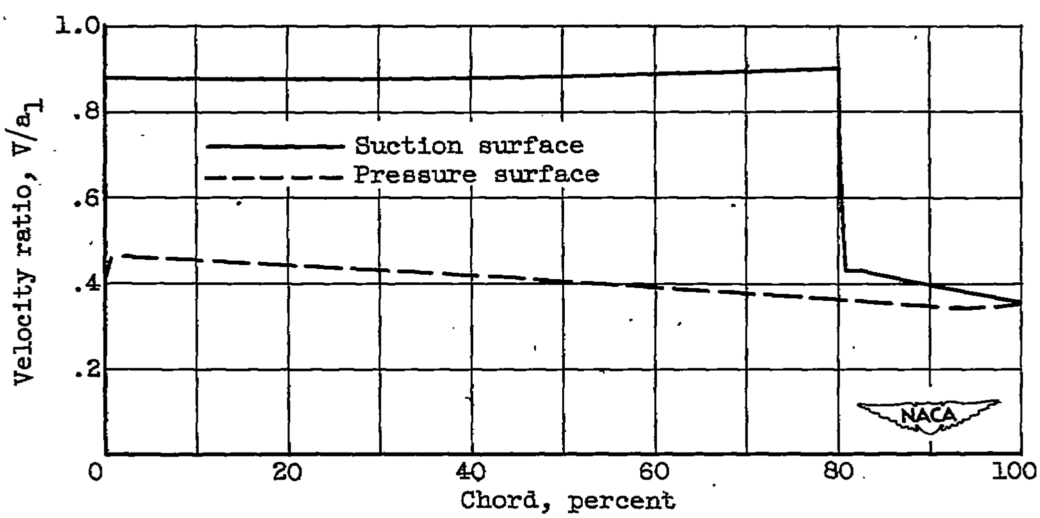


Figure 4. - Two-dimensional potential-flow velocity distribution on hub section of stator blade.

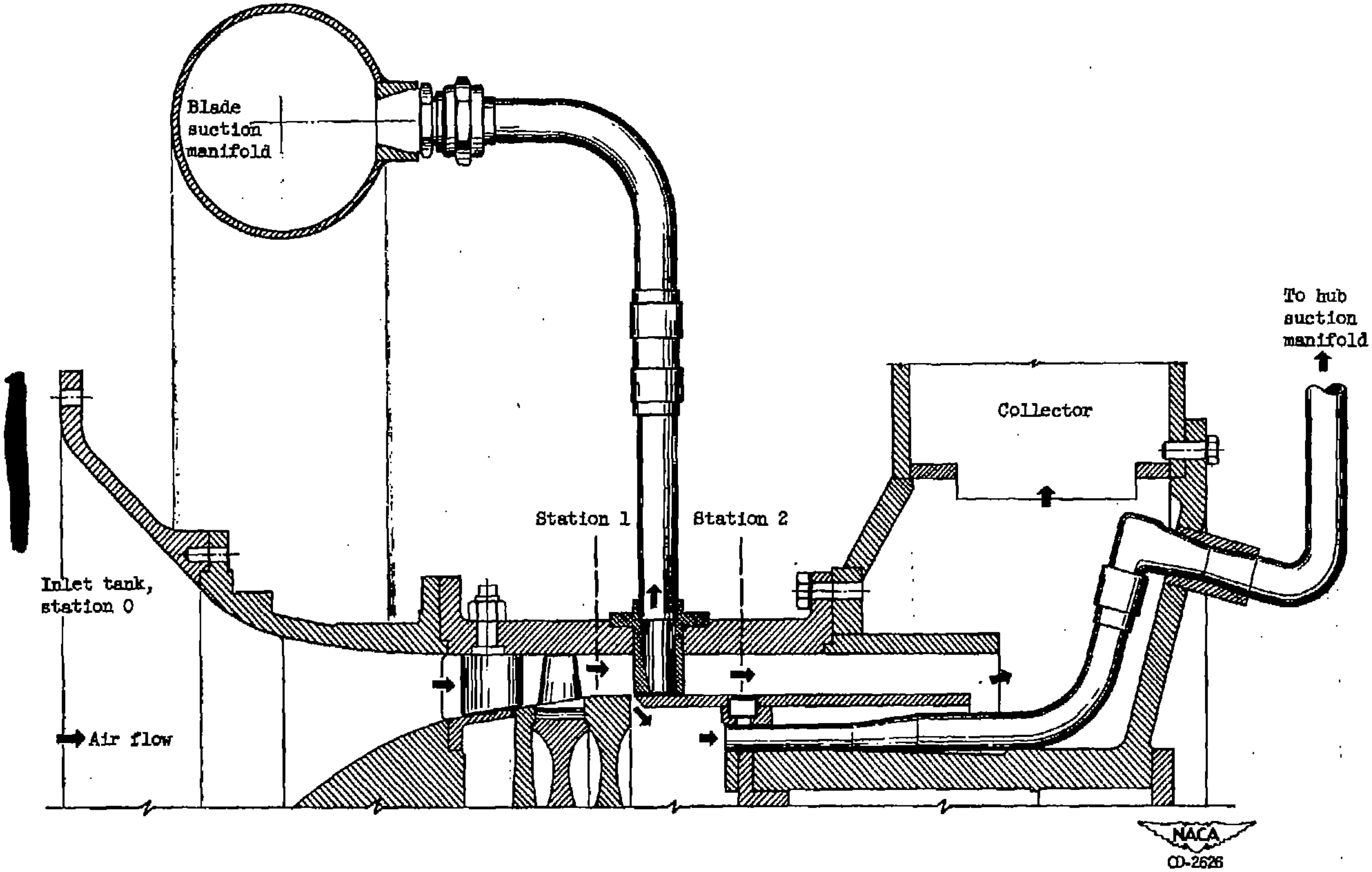


Figure 5. - Cross section of compressor flow passage.

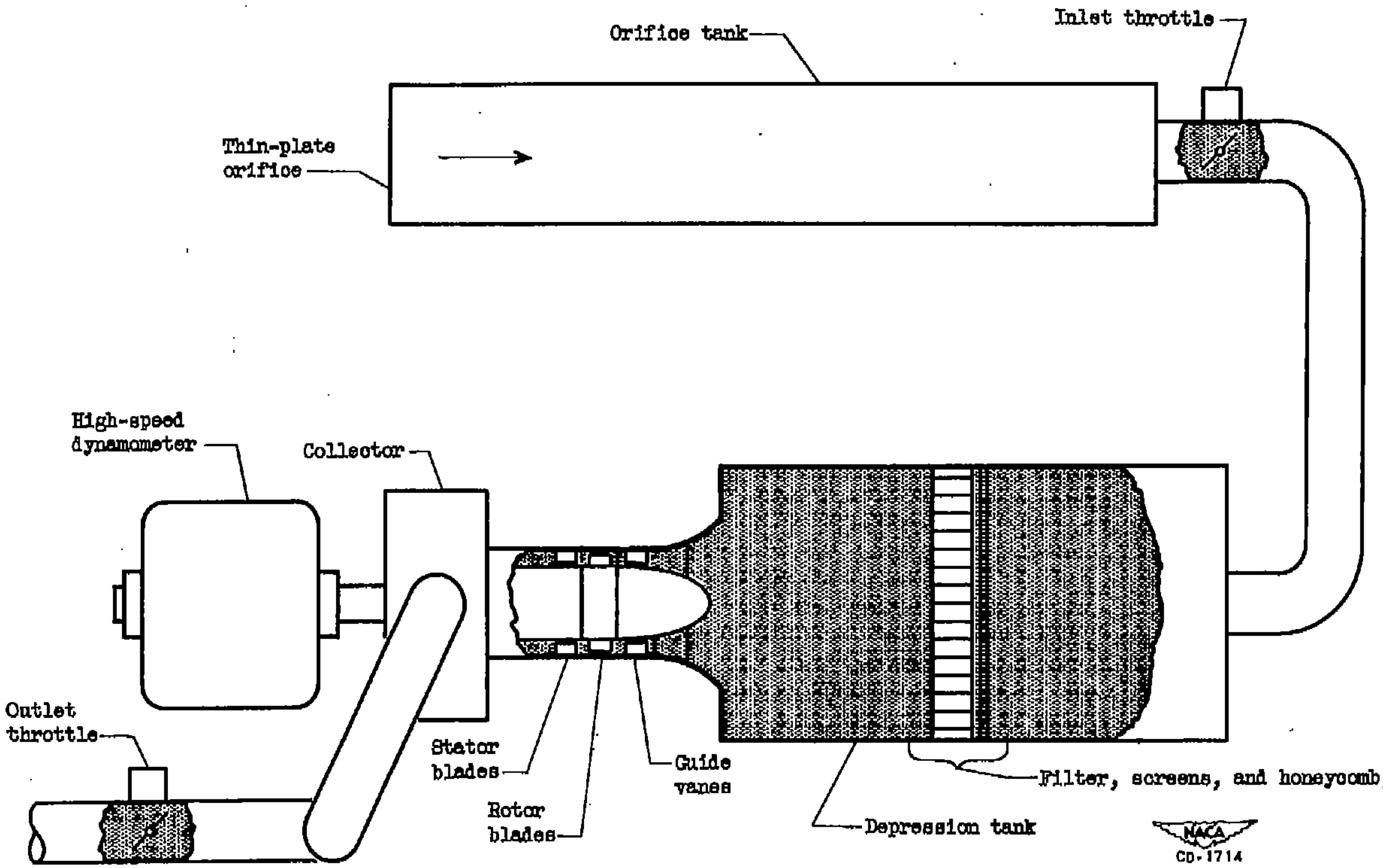


Figure 6. - Compressor installation.

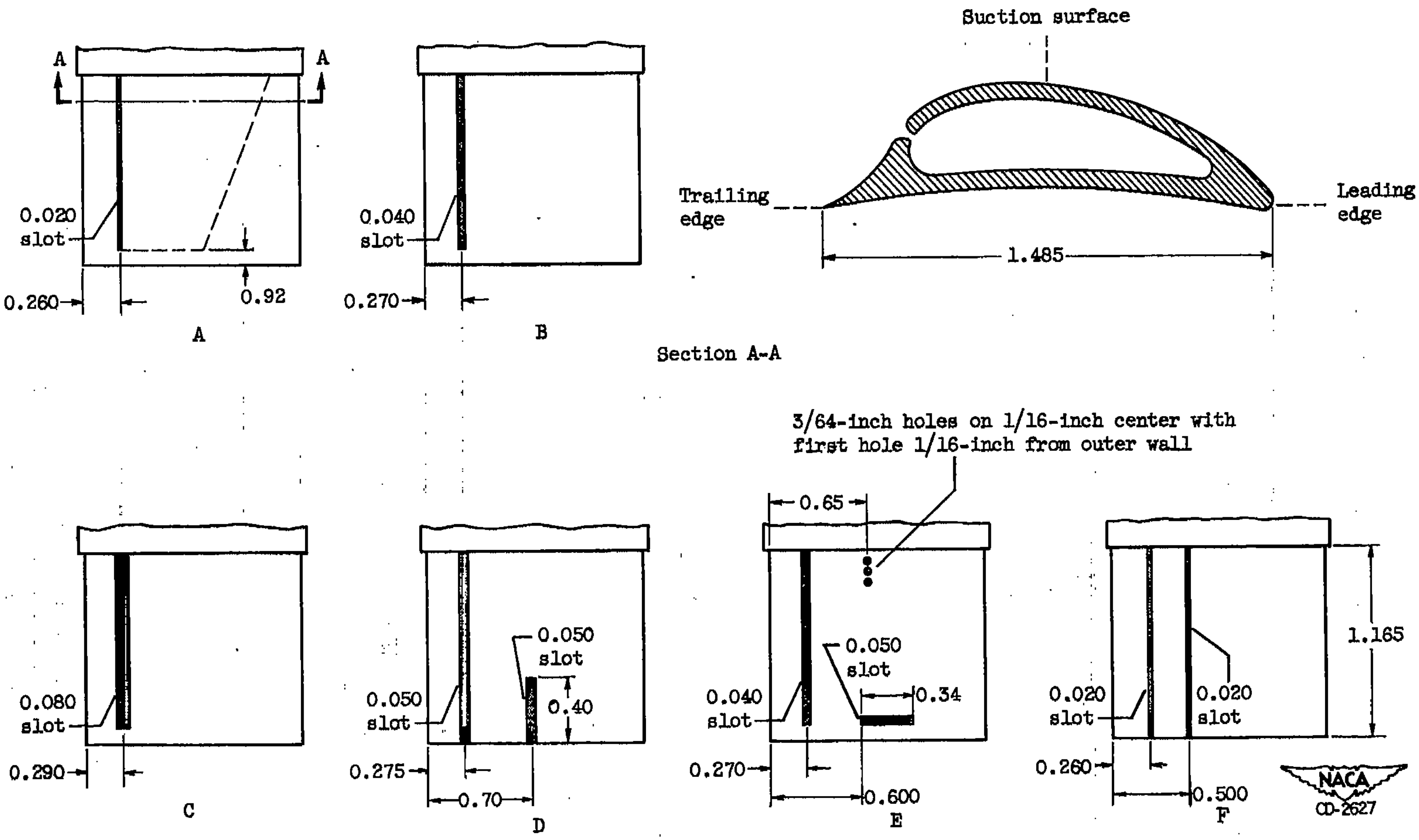
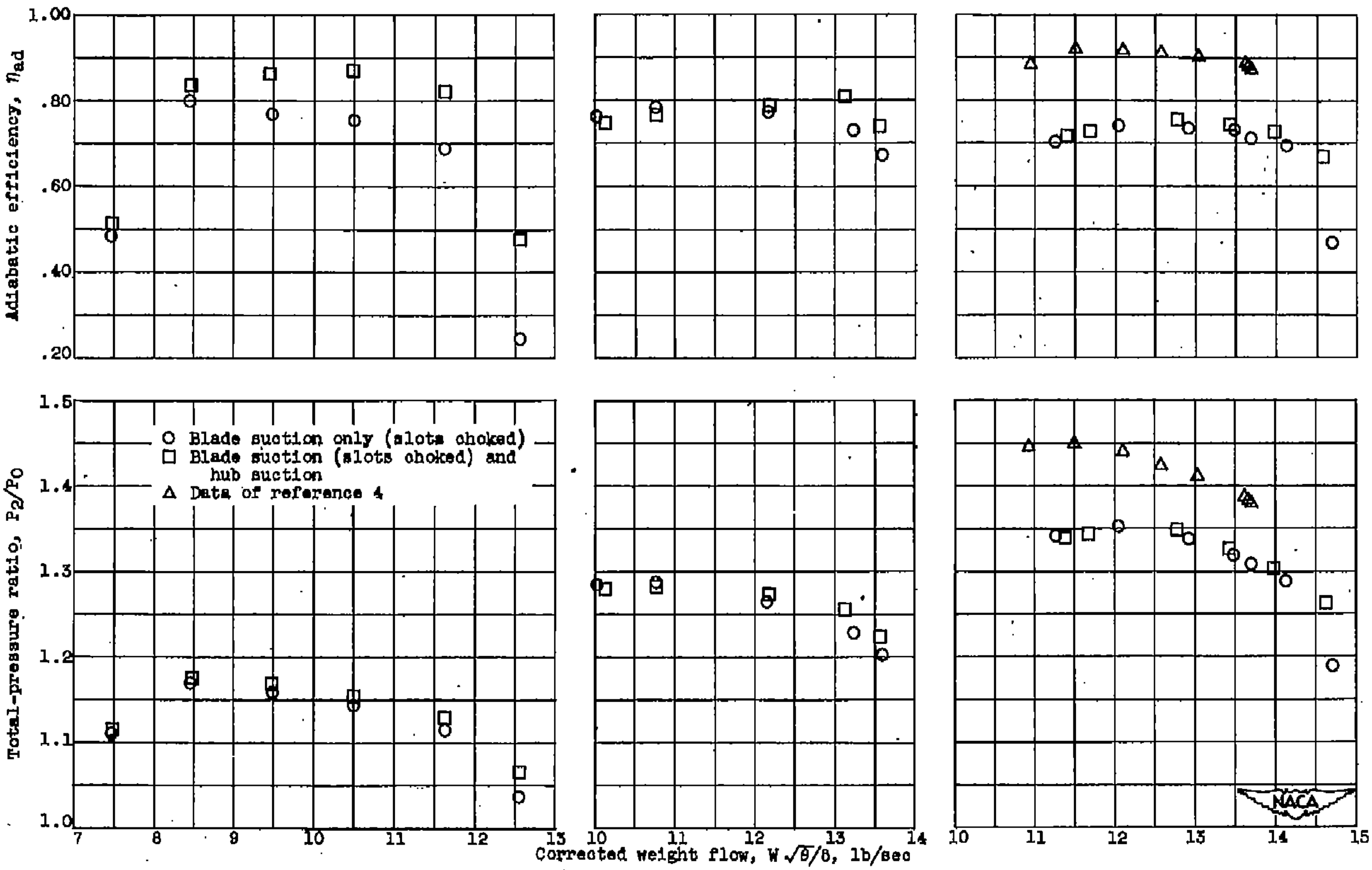


Figure 7. - Suction slot configurations.

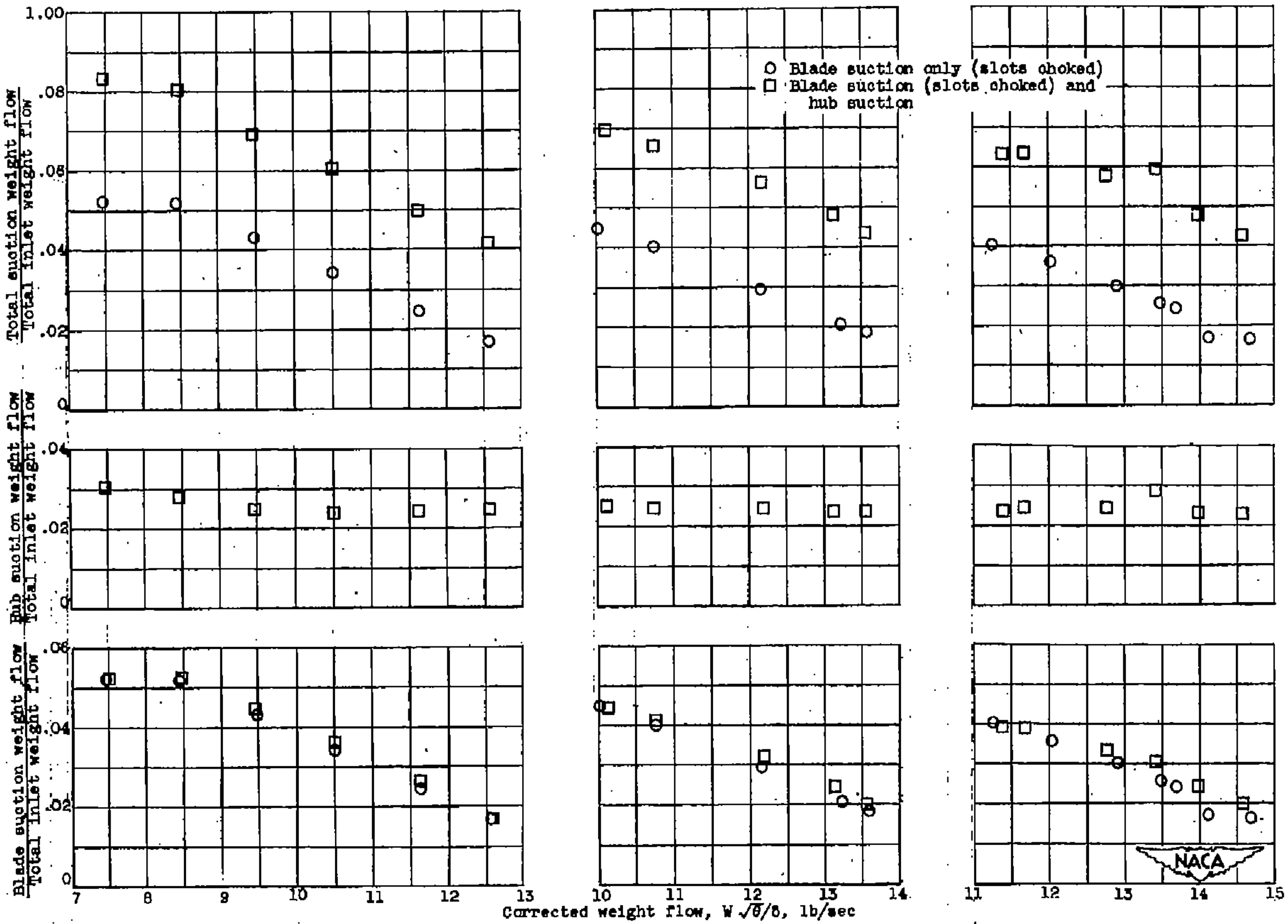


(a) Equivalent tip speed, $U_t/\sqrt{\theta}$, 585 feet per second.

(b) Equivalent tip speed, $U_t/\sqrt{\theta}$, 753 feet per second.

(c) Equivalent tip speed, $U_t/\sqrt{\theta}$, 836 feet per second.

Figure 8. - Variation of total-pressure ratio and efficiency with compressor weight flow for three tip speeds.



(a) Equivalent tip speed, $U_t/\sqrt{\theta}$, 585 feet per second.

(b) Equivalent tip speed, $U_t/\sqrt{\theta}$, 753 feet per second.

(c) Equivalent tip speed, $U_t/\sqrt{\theta}$, 836 feet per second.

Figure 9. - Variation of suction weight flows with compressor weight flow for three tip speeds.

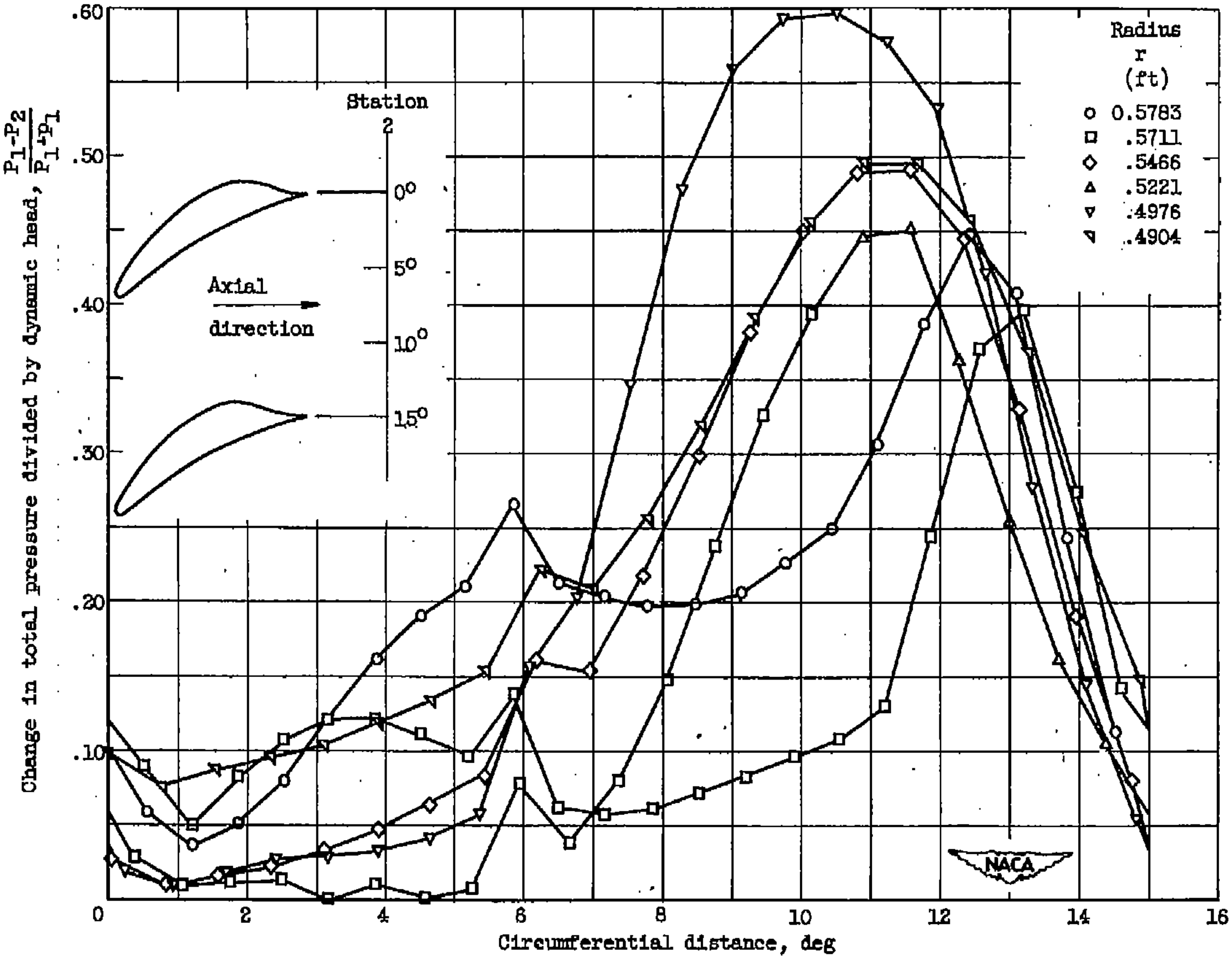


Figure 10. - Stator-loss survey. $U_t/\sqrt{\theta}$, 836 feet per second; $W\sqrt{\theta}/\delta$, 13.47 pounds per second; blade suction weight flow, 0.35 pound per second; without hub suction.

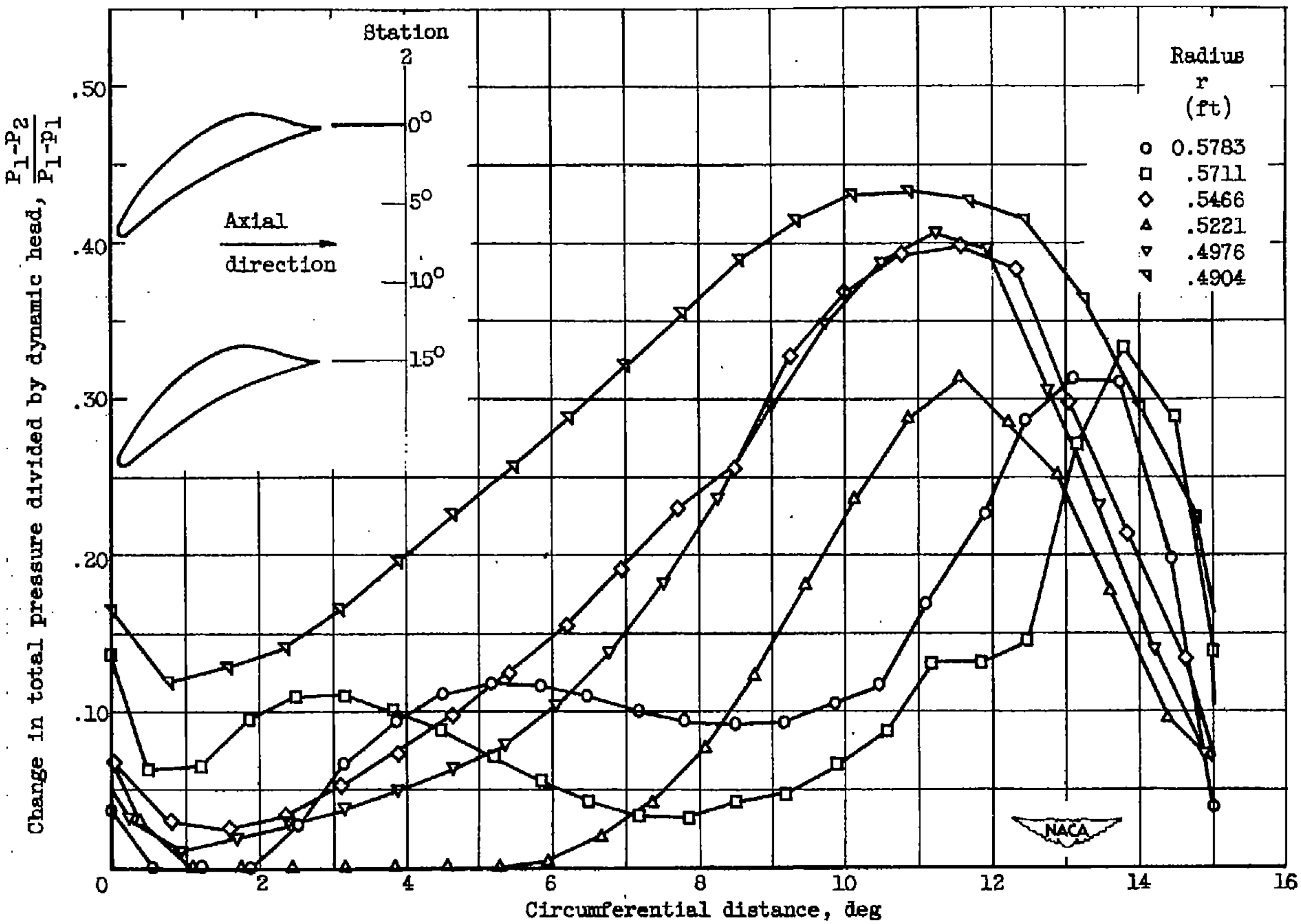


Figure 11. - Stator-loss survey. $U_t/\sqrt{\theta}$, 836 feet per second; $W\sqrt{\theta}/\delta$, 13.42 pounds per second; blade suction weight flow, 0.39 pound per second; hub suction weight flow, 0.41 pound per second.

[redacted]

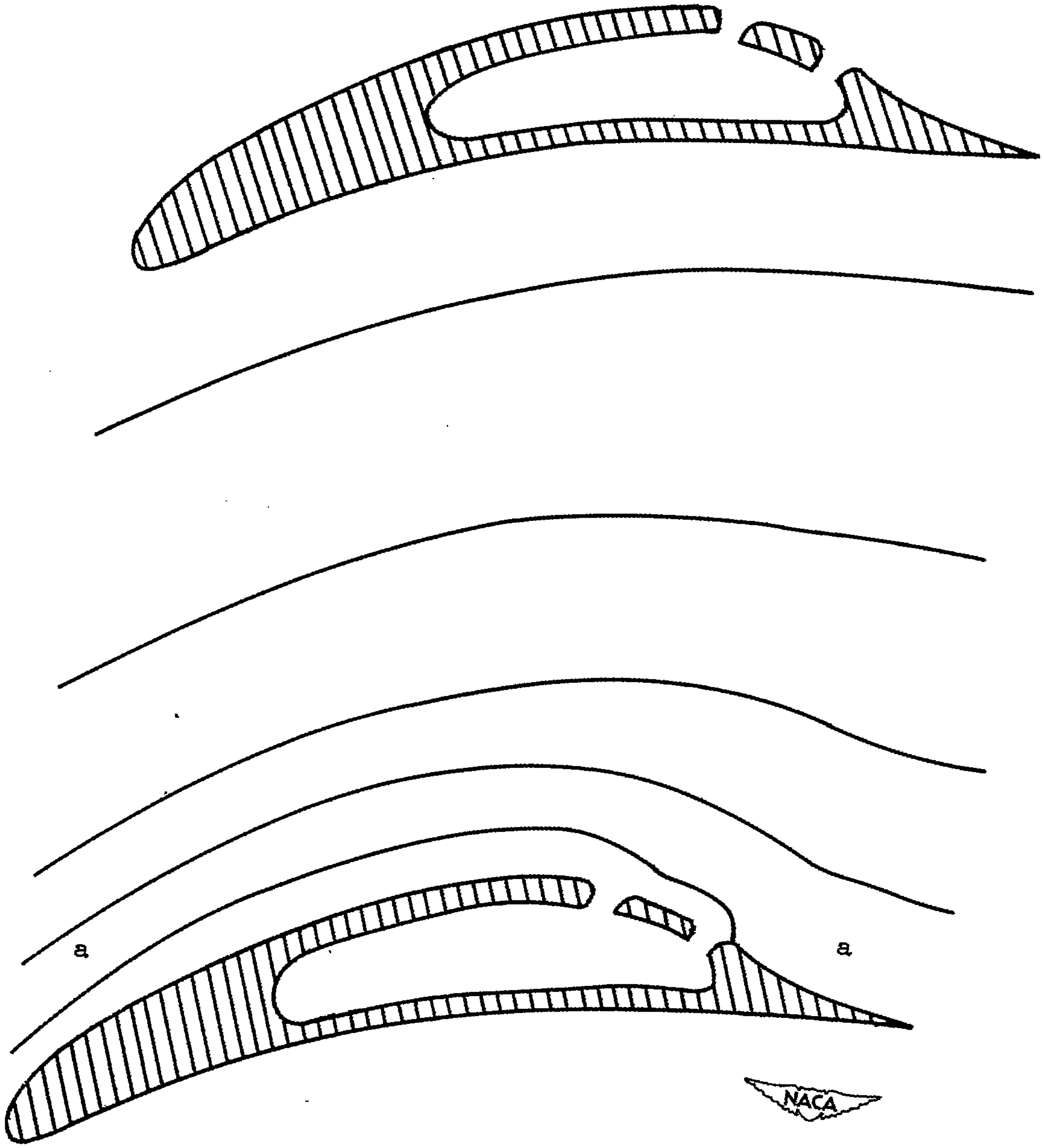


Figure 12. - Approximate streamlines in two-dimensional potential flow past hub section of stator blade.

[redacted]

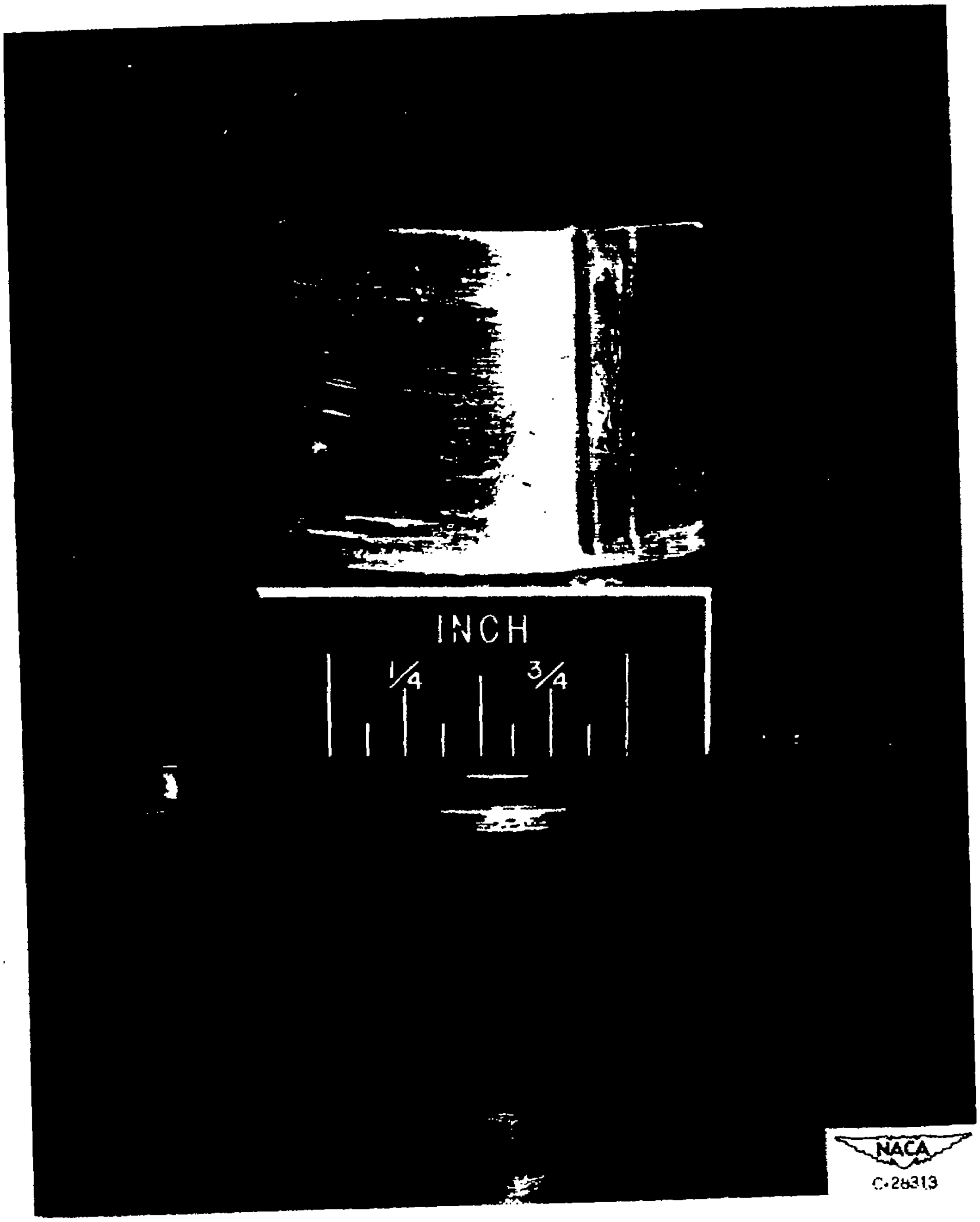


Figure 13. - Flow traces on blade without blade suction.

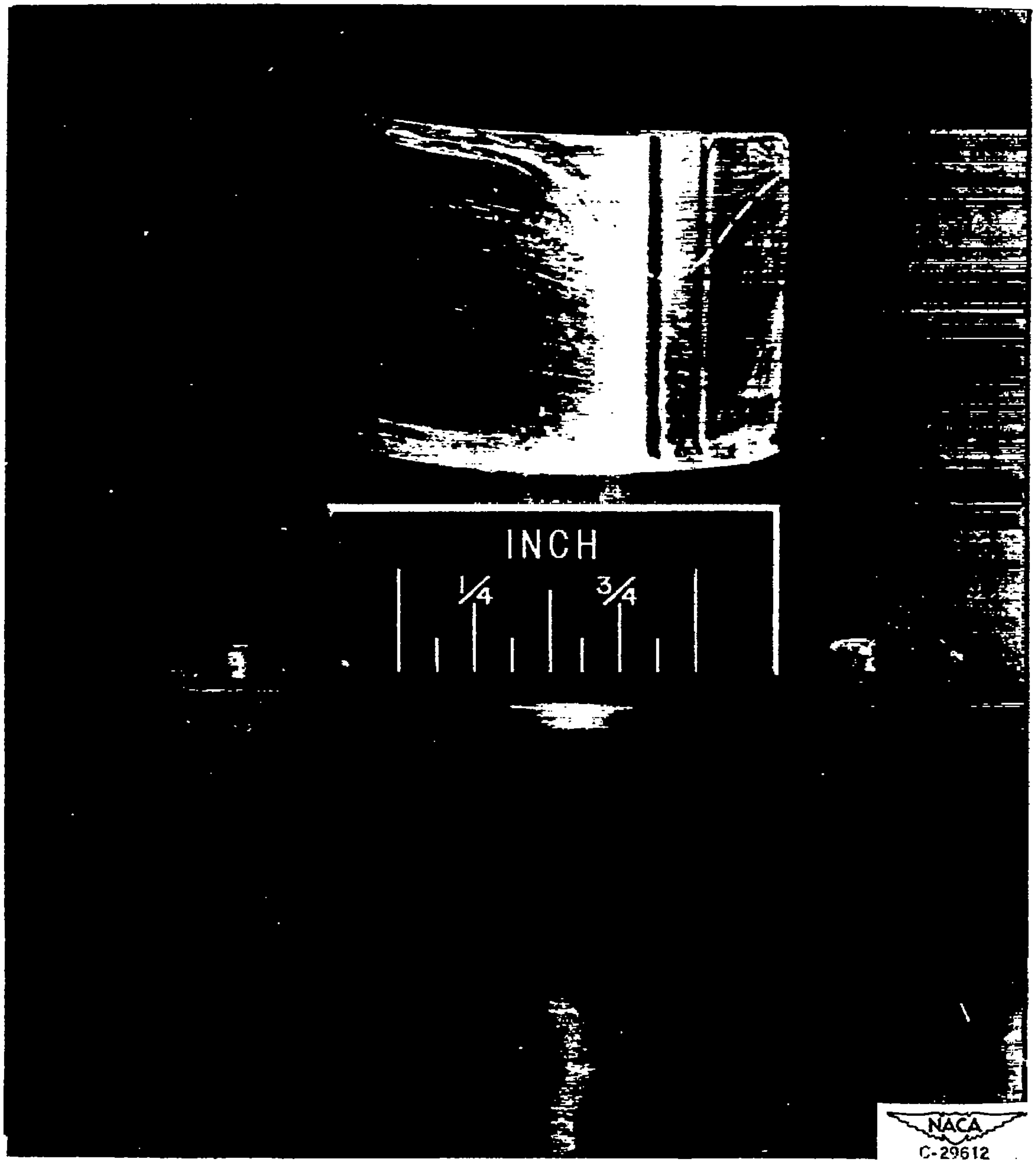


Figure 14. - Flow traces on blade with blade suction.

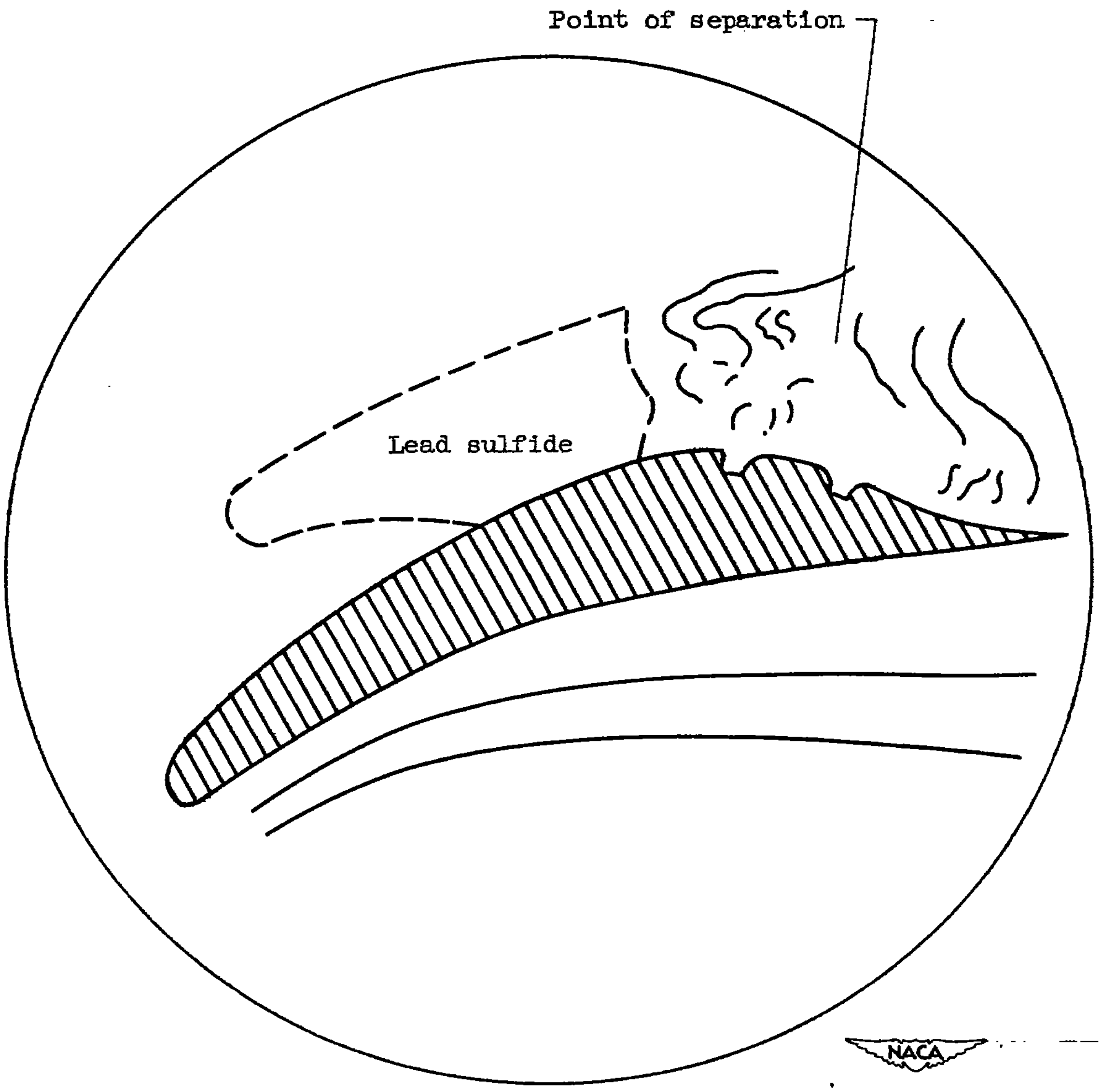


Figure 15. - Sketch of lead sulfide traces on inner case.

NACA-Langley - 6-27-52 - 350

SECURITY INFORMATION

[redacted]

[redacted]